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DOI: https://doi.org/10.3758/s13415-013-0175-5

Originally published at:
Kaiser, Stefan; Simon, Joe J; Kalis, Annemarie; Schweizer, Sophie; Tobler, Philippe N; Mojzisch, Andreas (2013). The cognitive and neural basis of option generation and subsequent choice. Cognitive, affective, behavioral neuroscience, 13(4):814-829.
DOI: https://doi.org/10.3758/s13415-013-0175-5

Cogn Affect Behav Neurosci (2013) 13:814–829
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The cognitive and neural basis of option generation and subsequent choice

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Published online: 29 May 2013

Abstract Decision-making research has thoroughly investigated how people choose from a set of externally provided options. However, in ill-structured real-world environments, possible options for action are not defined by the situation but have to be generated by the agent. Here, we apply behavioral analysis (Study 1) and functional magnetic resonance imaging (Study 2) to investigate option generation and subsequent choice. For this purpose, we employ a new experimental task that requires participants to generate options for simple real-world scenarios and to subsequently decide among the generated options. Correlational analysis with a cognitive test battery suggests that retrieval of options from long-term memory is a relevant process during option generation. The results of the fMRI study demonstrate that option generation in simple real-world scenarios recruits the anterior prefrontal cortex. Furthermore, we show that choice behavior and its neural correlates differ between self-generated and externally provided options. Specifically, choice between self-generated options is associated with stronger recruitment of the dorsal anterior cingulate cortex. This impact of option generation on subsequent choice underlines the need for an expanded model of decision making to accommodate choice between self-generated options.

Keywords Decision making · Option generation · Anterior prefrontal cortex · Anterior cingulate cortex · Take-the-first heuristic

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The cognitive and neural basis of option generation and subsequent choice

Research on decision making has made considerable progress with respect to the evaluation and selection of choice options (Glimcher & Rustichini, 2004; Rangel, Camerer, & Montague, 2008). These approaches presuppose a set of externally provided options and do not address the question of where the options come from in the first place. This does not pose a problem when decision making is investigated in well-constrained experimental environments (e.g., in the case of a lottery choice experiment). However, a serious problem arises when real-world complexity is approached, where most decision situations are underconstrained. In this type of situation, options are not directly provided by the environment but have to be generated by the agent. To illustrate, imagine that you miss your train and have to spend 1 h waiting for the next train. Quite obviously, before making a decision about how to spend this waiting time, you first have to generate options for what you could possibly do. Therefore, we and others have suggested that option generation should be included in decision-making models as a predecisional stage (Fellows, 2004; Kalis, Mojzisch, Schweizer, & Kaiser, 2008; Porcelli & Delgado, 2009; Smaldino & Richerson, 2012) (see Fig. 1a).

The present work employs a neurocognitive approach to provide empirical support for an expanded model of decision making by addressing option generation and its impact on subsequent choice. First, we assess the cognitive and neural correlates of option generation. Second, we test the hypothesis that choice behavior and its neural correlates differ between self-generated and externally provided options. Confirmation of the latter hypothesis would strongly imply that decision-making research must broaden its focus to accommodate decisions about self-generated options in ill-structured situations.

Although some proposals concerning the cognitive processes associated with option generation have been made, empirical research is limited (Keller & Ho, 1988). It is generally assumed that option generation is a form of memory search and retrieval, but the relationship between performance on option generation and long-term memory retrieval tasks has not been empirically addressed (Johnson & Raab, 2003; Klein, Wolf, Militello, & Zsambok, 1995). A further question is to what extent these cognitive processes depend on the agent's experience with the particular type of situation (Raab & Johnson, 2007; Ward, Suss, Eccles, Williams, & Harris, 2011). For example, it has been suggested that option generation in unfamiliar situations could tap more strongly into the processes underlying creative cognition (Kalis et al., 2008; Keller & Ho, 1988).

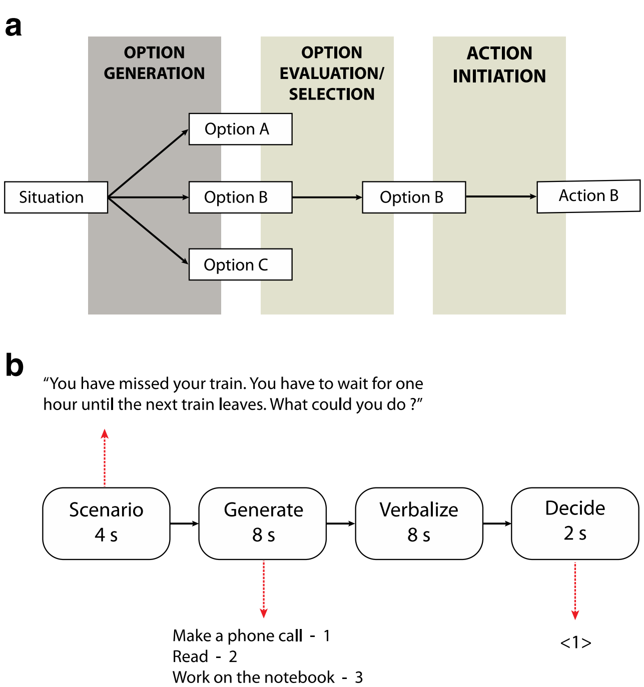

Fig. 1 **a** Option generation as a predecisional stage within a stage model of decision making. In the model, outcome evaluation and related feedback loops are omitted for clarity. **b** Trial structure of the option generation task. Numbers indicate buttonpresses

A related line of neuropsychological research has focused on problem solving in ill-structured situations. It has been well established that patients with lesions of the prefrontal cortex (PFC) may show marked difficulties in this type of situation despite intact functioning in most cognitive domains (Burgess, 2000; Channon & Crawford, 1999; Goel, Grafman, Tajik, Gana, & Danto, 1997). Most of these studies have not specifically addressed the generation of possible solutions, but Channon and Crawford demonstrated a significant impairment of this stage in patients with broadly defined anterior brain lesions. More recently, the role of the anterior PFC in solving ill-structured problems has been more strongly emphasized, although its putative function certainly extends beyond the generation of possible action sequences (Burgess, Alderman, Volle, Benoit, & Gilbert, 2009).

In the present study, we hypothesize that in most situations, option generation relies on the retrieval of options from long-term memory (Keller & Ho, 1988). However, the type of memory search and retrieval should be heavily dependent on situational and personal factors. When an agent has high expertise and/or the situation is highly constrained (e.g., a professional handball player in a game situation), the memory search will mainly rely on automatic processes. With decreasing expertise and/or constraints, an increasing amount of control over memory retrieval will be required. This distinction between automatic and controlled memory search should also be reflected in the neural correlates of option generation. It has been suggested that memory retrieval with a high demand on control processes might rely on the anterior PFC (Gilbert et al., 2006). Thus, we would expect the latter brain region to be activated when options are generated in ill-structured everyday situations.

The second important issue concerns the impact of option generation on subsequent choice behavior and its neural correlates. Regarding choice behavior, it has been previously suggested that "take-the-first" is an efficient heuristic for decisions between self-generated options (Johnson & Raab, 2003; Klein et al., 1995). Building on models of bounded rationality (Gigerenzer & Goldstein, 1996), this approach assumes that the first option generated is usually considered the best and is, therefore, more commonly selected than subsequently generated options. A comparison of choice behavior between self-generated versus externally provided options has not been performed. For the neural level, previous research on intentional or self-generated action has emphasized the role of medial prefrontal areas (Passingham, Bengtsson, & Lau, 2010; Walton, Devlin, & Rushworth, 2004). However, in this body of research, free selection was generally restricted to predefined option sets that were provided by the experimenter, but no active generation of options was required prior to selection. Furthermore, the impact of option generation on the neural correlates of subsequent decisions has not been addressed so far.

Finally, previous work on option generation has often focused on specific situational contexts. Typical examples are option generation for the ball-handling player in sports, for law enforcement officers (Ward et al., 2011), or for management problems (Adelman, Gualtieri, & Stanford, 1995; Johnson & Raab, 2003). The importance of this research notwithstanding, it is not clear whether the results from these specific situations generalize to everyday decision making.

In the present study, we developed a new experimental task to address option generation in real-world situations. In this task, participants were presented with a series of short vignettes reflecting ill-structured everyday situations (Fig. 1b). They were required to silently generate options for action in the respective situation and to indicate by buttonpress each time they generated an option. Subsequently, participants had to verbalize the generated options and then select their preferred option out of the generated option set.

We first performed a behavioral study with healthy students (N = 52) and, thereafter, conducted a functional magnetic resonance imaging study (N = 19) to address the following research aims: (1) to define the cognitive and neural correlates of option generation and (2) to assess whether choice behavior and its neural correlates differ between self-generated and externally provided options.

Study 1

Method

Participants

Fifty-two undergraduate students (34 female; mean age = 22 years, range = 19–30 years, SD = 2.31) were recruited from the University of Göttingen. The study was approved by the institutional review board, and all participants gave written informed consent after the procedure had been fully explained.

Option generation task

Participants performed a computer-based task implemented in Presentation (Neurobehavioral Systems Inc., Albany, NY). All stimuli were visually presented on a notebook screen. Responses were recorded via a microphone connected to the stimulation computer. The trial structure is described in Fig. 1b. In the option generation task, participants were visually presented with short real-world scenarios on a computer screen (see the Appendix for a list of the scenarios employed). Immediately thereafter, they had to generate options for action in this situation and indicate generation of each option by a buttonpress. Participants were given 8 s for this option generation phase. In this phase, only the word “generate” was visible on the computer screen. They then had to verbalize the previously generated options. Finally, participants were instructed by the word “decide” presented on the computer screen to select the preferred option out of the options they had generated before. Selection was indicated via buttonpress. Between trials, a fixation cross was presented. Participants performed 10 test trials to familiarize themselves with the task. In the main part of the experiment, 70 scenarios were presented. After the last trial, participants were again presented with all 70 scenarios and were asked to rate the familiarity of each scenario on a 9-point Likert scale. To assess the impact of familiarity, we later performed a median split for each participant, thus dividing familiar and unfamiliar scenarios. The experimental session, including the practice trials, took about 30 min to complete.

Cognitive test battery

Participants were asked to perform five different cognitive tests in order to assess long-term memory performance, creative problem solving, creative idea generation, verbal fluency, and cognitive set shifting. The performance in these tasks was later correlated with the performance in the option generation task. Specifically, the following cognitive tests were employed.

1. Verbal Learning and Memory Test (Helmstaedter, Lendt, & Lux, 2001): This test was used to asses long-term memory performance. Participants had to learn a list of 15 words. In the original test, the list is repeated 5 times. To avoid ceiling effects in our healthy participants, we presented only three learning trials. After learning, an interference list was presented. Free recall was assessed after both interference and a 15-min delay. Outcome measures employed here were free recall after delay and, as a more specific measure of retrieval, the difference between recalled items after delay and recalled items after learning.
2. Remote Associates Test (RAT; Mednick, 1962): The RAT was employed to measure creative problem solving. Each RAT item consisted of three stimulus words (e.g., *board*, *magic*, and *death*) that were more or less strongly linked to a target word (e.g., *black*). On each trial, participants were presented with three stimulus words and were asked to determine the target word. The variable of interest was the number of correct solutions. We used a modified version of the original RAT, comprising 16 trials. Participants were free to allocate as much time as they needed for each trial but had to finish the whole test within 15 min.
3. Product names task (Marsh, Ward, & Landau, 1999): In this test of creative generation, participants were asked to create new labels for new products and were exposed

to benchmark examples that have been shown to compromise the generation of unique and new ideas (Rubin, Stoltzfus, & Wall, 1991). Specifically, participants were instructed to create up to three new labels for each of the three categories of products (*pasta*, *nuclear element*, *pain reliever*). For each of the categories, the benchmark examples provided had two common endings. Creative output was operationalized in terms of the number of product names created for each category that did not share the word endings of the examples. There was no time limit for this task.

4. Verbal fluency tasks (Aschenbrenner, Tucha, & Lange, 2001): Participants performed a category fluency task, in which they were asked to name as many animals as possible within 1 min. They also performed a letter fluency task, in which they were required to produce as many words that began with the letter "S" as possible within 1 min.
5. Plus–minus task : In order to measure cognitive set shifting, participants performed the plus–minus task, which was adapted from Spector and Biederman (1976). The task consisted of three lists of 30 two-digit numbers on a single sheet of paper. On the first list, participants were asked to add 3 to each number and write down their answers. On the second list, participants were required to subtract 3 from each number. Finally, on the third list, participants had to alternate between adding 3 and subtracting 3 (i.e., they had to add 3 to the first number, subtract 3 from the second number, and so on). List completion times were measured by a stopwatch. The cost of cognitive set shifting was calculated as the difference between the time to complete the alternating list and the average of the times to complete the addition and subtraction lists.

Results

For the option generation phase, the main dependent variable was the quantity of options generated. This variable was entered into bivariate Spearman correlations with the cognitive performance indices described above. For the decision phase, we extracted the frequency for each position of the selected option (e.g., first, second, and so on). For all comparisons including these variables, we employed nonparametric Wilcoxon tests. Throughout, significance level was set to $p < .05$.

Quantity of generated options

Participants generated a mean of 2.97 options across all scenarios (SD = 0.7). As was expected, the quantity of options generated was significantly higher in familiar than in unfamiliar scenarios, $t(48) = 3.92$, p < .001. Two participants did not complete the familiarity ratings.

Correlations between option generation and other cognitive processes

The mean number of generated options was positively correlated with retrieval performance on the Verbal Learning and Memory Test (Fig. 2a, b). Specifically, a significant positive correlation was observed for both free recall after delay and a more specific measure of retrieval, which was defined as the difference between recall after delay and recall after learning. In contrast, there was no correlation between option generation performance and the two different measures of creative cognition (Fig. 2c, d), which included the Remote Associates Test and the product names task. Furthermore, the quantity of generated options was significantly correlated with the generated items in the category fluency task, $r = .33$, $p < .05$, but not in the letter fluency task, $r = .22$, $p > .1$. Finally, the quantity of generated options was not significantly correlated with performance on the set-shifting task (all $ps > .1$).

Furthermore, we addressed whether this pattern is dependent on the participants' self-rated familiarity with the scenario. Our results showed that the correlational structure was similar for familiar und unfamiliar scenarios. Correlations between number of options generated and long-term memory retrieval, as well as category fluency, remained significant for both familiar and unfamiliar scenarios (all ps < .05). Additionally, the correlation of generated options with measures of creative cognition, letter fluency, and set shifting was not significant for either familiar or unfamiliar scenarios (all ps > .1).

Option selection

We asked whether participants would employ the take-the-first heuristic when deciding between self-generated options. Independently of the number of options generated, participants were significantly more likely to select the first option out of the generated option set than all subsequent options (all ps < .01; see Fig. 3), thereby supporting the take-the-first heuristic.

To summarize, the results from our behavioral study suggest that option generation in simple real-world settings is associated more with retrieval from long-term memory and category fluency than with creative cognition, letter fluency, and executive functions. This correlation pattern was not affected by the familiarity of the scenario. In the General Discussion section, we will discuss these findings in relation to the results of the fMRI study.

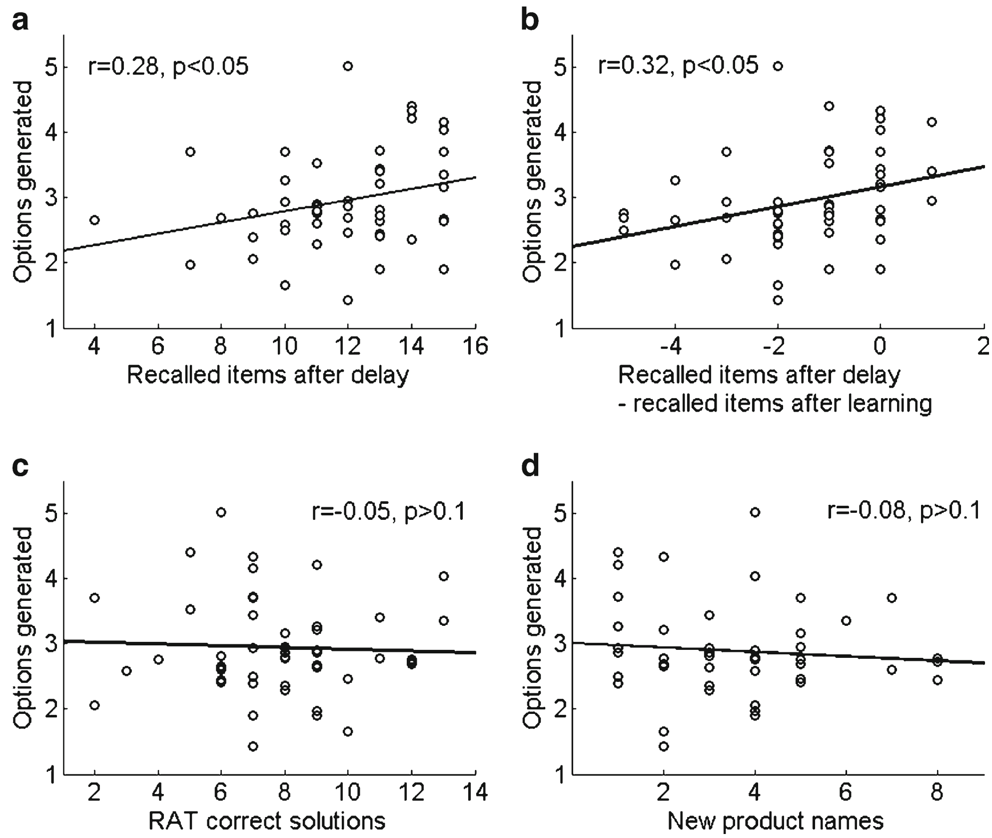

Fig. 2 Correlations between amount of generated options and performance on tasks of long-term memory (panels a and b) and creative cognition (panels c and d). **a** Free recall from long-term memory after delay. **b** A more specific measure of retrieval calculated as free recall from long-term memory − free recall after learning. **c** Correct solutions on the Remote Associates Test. **d** Newly generated items on the Product Names Test

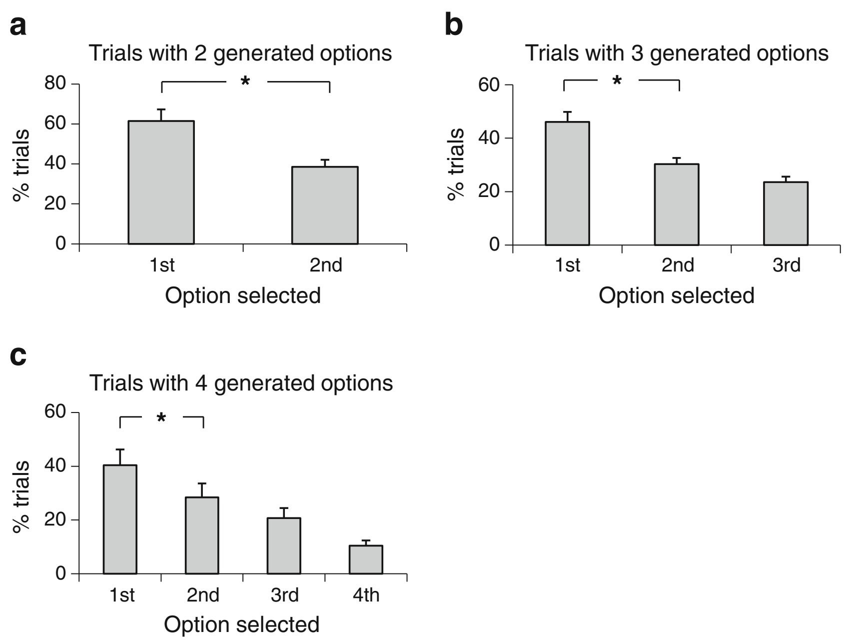

Fig. 3 Patterns of choice between self-generated options in the behavioral study. Participants selected the first option significantly more often than subsequently generated options. This effect can be found in trials with two, three, and four generated options

Study 2

Study 2 had two aims. First, we sought to examine the neural correlates of option generation. Second, we aimed to assess whether the neural correlates of decision making differ when deciding between self-generated and externally provided options. The same experimental task was employed as in Study 1, with a few modifications (see below).

Method

Participants

Twenty undergraduate and graduate students were recruited from the University of Heidelberg. One participant had to be excluded because of inappropriate responses in the decision phase (i.e., selecting options that had not been generated). This left 19 participants (12 female; mean age = 25.8 years, range = 21–34 years, SD = 4.1) for the final analysis. The study was approved by the institutional review board, and all participants gave written informed consent after the procedure had been fully explained.

Option generation task

For the fMRI study, we modified the option generation task employed in Study 1 (see Fig. 4). Importantly, we introduced a control condition that was not employed in Study 1. In this control condition, after presentation of the scenario, participants were required to read and memorize a set of options, which were visually presented. Participants were required to press a button each time an option was presented. Subsequently, repetition of, and decision between, the options were required exactly as in the active condition. In both conditions, the chosen option was indicated by a buttonpress. In the fMRI task, participants were not required to overtly verbalize the options in order to avoid excessive motion. Thus, participants were instructed to silently repeat the options that were either generated during the preceding generation phase (active condition) or presented during the preceding reading phase (control condition).

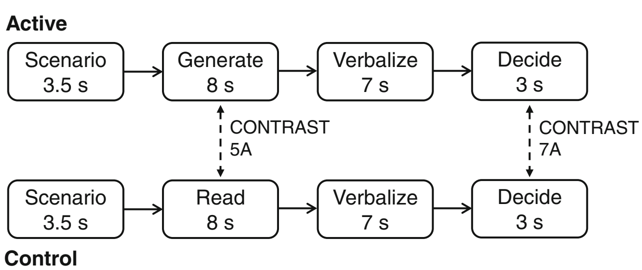

Fig. 4 Modified option generation task for fMRI showing the main contrasts for option generation (results in Fig. 5a) and subsequent option selection (results in Fig. 7a)

The timing of the trial phases was slightly modified from the behavioral study on the basis of the behavioral results and the participants' reports. The scenario presentation was shortened to 3,500 ms because participants in the behavioral study reported having started the option generation process during the presentation phase in some scenarios. The duration of the generation phase remained unchanged. The verbalization phase was shortened to 7,000 ms, which was clearly sufficient for silently repeating all options. Finally, the decision phase was increased to 3,000 ms, because participants reported that if the time span had been shorter, they would have started the decision process before this phase. The intertrial interval varied between 2 and 8 s, following a normal distribution with a mean of 5 s. During the intertrial interval, a fixation cross was shown. There were no other rest or fixation periods.

Sixty out of the 70 scenarios used in the behavioral study were selected for the fMRI study. We deleted 7 scenarios in which 5 or more participants did not generate any option. In addition, we deleted 3 scenarios that participants considered difficult to understand. Participants performed the task in two scanning runs with 30 scenarios, resulting in an approximate duration of 13 min for each run. In each run, participants were given four groups of scenarios in counterbalanced sequence (i.e., either active–control–active–control or control–active–control–active).

For each participant, the scenarios were randomly distributed between the active and control conditions. Externally provided options for the control condition were drawn from options created by participants in the behavioral study. Options were pooled across participants from Study 1, and commonly generated options were selected for the fMRI study in order to avoid presenting the participant with very unfamiliar options. Two to 4 options, with a mean of 3 options, were presented per trial to ensure that the number of available options was similar in the active and control conditions. In the active condition, participants created a mean of 3.15 options, which was not significantly different from the mean of 3 options in the control condition ($p > .1$).

Image acquisition

Images were acquired with a Siemens Trio 3 Tesla scanner equipped with a standard single-channel head coil. We used a rapid echo-planar imaging sequence covering the whole brain with the following parameters: TR 2 s, TE 30 ms, 80° flip angle, 33 slices, transverse orientation, slice thickness 4 mm, in-plane resolution 3.4 × 3.4 mm. In addition, a high-resolution sagittal T1-weighted three-dimensional data set was acquired with the following parameters: 176 slices, voxel size 1 × 1 × 1 mm, TR 11 ms, TE 4.92 ms, 15° flip angle.

Image analysis

Data analysis was performed with SPM8 (FIL, London, http://www.fil.ion.ucl.ac.uk/spm/) implemented in MATLAB 7 (Mathworks, Sherborn). Functional images were checked for artifacts and were realigned to account for head movement. Head movements did not exceed the voxel size of 3.4 mm in any direction. After coregistration, images were normalized to the MNI template with a final voxel size of 2 × 2 × 2 mm. Functional images were spatially smoothed with a kernel of 10 mm FWHM.

A general linear model (GLM) was fitted to the single-participant data that included separate regressors for each task phase (scenario, generate, verbalize, decide). This resulted in four regressors for the active condition and four regressors for the control condition. Regressors of interest represented the generation and decision phases (see Fig. 4). Regressors were modeled as boxcar functions convolved with the canonical hemodynamic response function. On the single-participant level, t-contrasts were calculated for comparison of regressors of interest between active and control conditions. For group analysis, these single-participant contrast images were entered into a hierarchical model equivalent to a random-effects model, as implemented in SPM. Since we aimed at sensitivity for spatially extended activation while controlling for multiple comparisons, we report results significant at a familywise cluster-level threshold of $p < .05$ (cluster defining threshold, $t = 3.61$, $p < .001$, uncorrected) (Friston, Holmes, Poline, Price, & Frith, 1996).

In order to further characterize the activation pattern of the anterior PFC, we employed a region of interest (ROI) analysis. The anterior prefrontal ROI was defined as a cluster that contained all suprathreshold voxels in the main contrast generate versus control during the generation phase (i.e., the region depicted in Fig. 5a). Mean percentage of signal change for each regressor of interest was extracted using Marsbar (marsbar.sourceforge.net). The baseline for the signal change calculation corresponds to the mean signal of all voxels in the respective ROI over the whole time course of the experiment. This resulting signal change was then entered as a dependent variable in a 2 × 2 repeated measures ANOVA with the factors of condition (active/control) and familiarity (high/low). Trials were divided into low- and high-familiarity scenarios according to the participant's ratings, which were obtained in the same way as in Study 1. The ROI analysis for this interaction was followed up by an exploratory whole-brain analysis at a familywise cluster-level threshold of $p < .05$.

In order to assess the neural correlates of the take-the-first heuristic, we separated trials on which the first option was selected from all other trials. We performed an ROI analysis of the left anterior prefrontal region analogous to the familiarity analysis described above. The resulting signal change was then entered as a dependent variable in a 2 × 2 repeated measures ANOVA with the factors of condition (active/control) and option selected (first/subsequent). The ROI analysis for this interaction was followed up by an exploratory whole-brain analysis at a familywise cluster-level threshold of $p < .05$.

In the GLM analysis described above, a critical issue is the potential correlation between the regressors modeling the trial phases. Therefore, we have performed an additional analysis employing finite impulse response functions (Henson & Friston, 2007), which assesses activation differences across trial phases without assuming the long duration of the hemodynamic response function. For this purpose, we divided the time after trial onset into 15 time bins of 2 s (TR) each. On the single-participant level, this yielded 30 contrasts modeling the time bins for each condition, which were entered into a hierarchical model equivalent to a random-effects model for group analysis. On the group level, we implemented a factorial design with the factors condition (generate/control) and time. We then calculated an F-contrast for the critical condition × time interaction.

For presentation of the results, significantly activated clusters were overlaid on the averaged T1-weighted images of all participants (Figs. 5a and 7a) using MRIcron (www.cabiatl.com/mricro/mricron/index.html). Time course plots of evoked responses for brain regions significantly activated in the whole-brain analysis were conducted using the rfxplot toolbox (Glascher, 2009).

Results

Quantity of generated options

Participants generated a mean of 3.1 options across all scenarios ($SD = 0.52$). As in Study 1, the quantity of options generated was significantly higher in familiar scenarios than in unfamiliar scenarios, $t(17) = 3.27$, $p < .01$.

Neural correlates of option generation

The task employed in the fMRI study allowed us to compare active generation of options with presentation of externally provided options (see Fig. 4 for contrast definition). In both conditions, subsequent verbalization and decision between the options was required. The contrast generation versus reading of options yielded a robust activation of the left anterior PFC at MNI coordinates −24/+50/+18, $t_{max} = 7.54$, cluster size = 464 voxels (Fig. 5a). The time course plot of the BOLD signal in this region (Fig. 5b) suggests an early separation of the two conditions, starting with the presentation of the scenarios and extending into the generation phase. No other brain regions were significantly activated at a whole-brain cluster-level corrected threshold. The reverse contrast comparing the control condition with the generate condition revealed extensive activation in posterior brain regions (see Table 1).

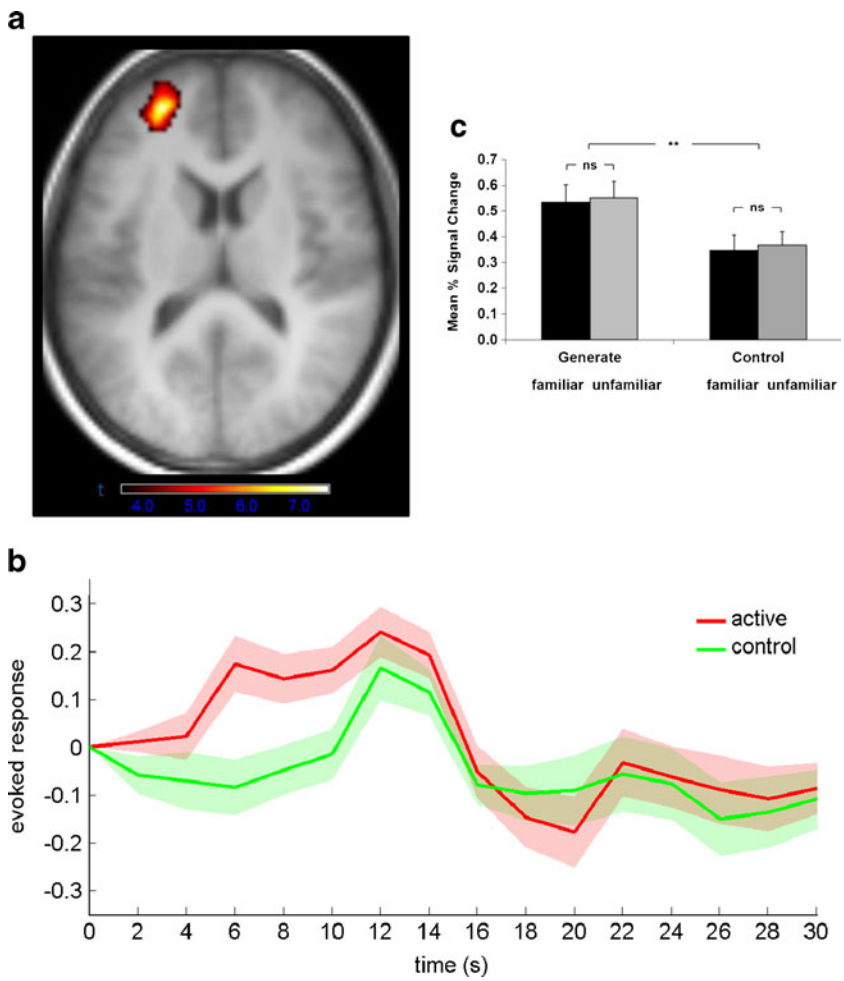

Fig. 5 **a** The contrast generate versus control yielded a robust activation of left anterior prefrontal cortex. Image thresholded at $p < .001$ uncorrected, only the cluster significant at family-wise cluster-level corrected threshold of $p < .05$ is shown. **b** Time course plot of evoked responses (percentage of signal change) for the anterior prefrontal region depicted in Fig. 5a. Shaded areas depict standard errors of means. **c** Mean percentage of signal change extracted from the left anterior prefrontal cortex region for each condition (generate/control) and familiarity (high/low). Error bars denote standard errors. We observed a main effect of condition but no main effect or interaction involving familiarity

We further examined whether activation patterns for option generation differed between familiar and unfamiliar scenarios. We performed an ROI analysis of the left anterior prefrontal region detected in the main analysis (Fig. 5c). We observed a main effect of condition, $F(1, 19) = 43.24$, $p < .001$, but no main effect or interaction involving familiarity, $F(1, 19) = 2.11$, $p > .1$; $F(1, 19) = 0.01$, $p > .1$. Also, in an exploratory whole-brain analysis at cluster-level corrected threshold, no differential recruitment was observed between high- and low-familiarity scenarios. Thus, we did not find any modulation of the brain activation pattern by familiarity.

Option selection for self-generated and externally provided options

We first addressed option selection for self-generated options. As in Study 1, participants were more likely to select

Table 1 Locations of significant activations in the control (read) versus active (generate) contrast during the generation phase at cluster-level threshold of $p < .05$ (MNI coordinates, cluster size, and *t*-statistic are given)

Brain Region	MNI Coordinates (*x*,*y*,*z*)	Cluster Size	*t*(18)
R middle/superior temporal middle/ inferior occipital	58 −4 −6	5,138	8.04
L superior parietal	−34 −56 52	431	7.74
R temporal pole/insula	46 16 −14	323	7.74
L middle temporal	−60 −14 −6	1,063	6.25
L temporal pole/insula	−40 16 −22	422	6.22
L middle/inferior occipital	−40 −84 −6	2,039	5.56
R inferior frontal/operculum	38 22 22	509	5.32

the first option out of the self-generated options than all subsequently generated options ($p < .01$; see Fig. 6). Thus, the take-the-first pattern from Study 1was confirmed.

In contrast, no choice preference for the first option was expected when options were externally provided. Our newly developed fMRI task allowed us to test this hypothesis by directly comparing choice behavior between self-generated and externally provided options. As was predicted, participants were more likely to select the first option for self-generated options than for externally provided options ($p < .05$; see Fig. 6). For externally provided options, participants were not more likely to select the first option than to select subsequent options (all ps $> .1$; see Fig. 6), in line with the notion that they did not apply a take-the-first heuristic.

Neural correlates of option selection

We further aimed to examine whether the neural correlates of the decision process differ between a choice among self-generated options and a choice among externally provided options. For this purpose, we calculated the contrast between the regressors for the decision phase in the generate condition and the decision phase in the control condition (see Fig. 4 for contrast definition). Our results showed that selection between self-generated options was associated with a signal increase in the dorsal anterior cingulate cortex (ACC) relative to selection between externallyprovided options at 4/+28/+26, $t_{\max} = 4.88$, cluster size = 196 voxels (Fig. 7a). No other brain region was significantly activated at a whole-brain cluster-level corrected threshold of $p < .05$.

The time course plot for this region in the dorsal ACC (Fig. 7b) revealed that the largest difference between active and control conditions occurred late in the trial in relation to the decision phase. In addition, ACC activation seems to occur somewhat earlier when participants select the first option. The reverse contrast comparing decisions between externally provided options with decisions between self-generated options did not reveal any activation significant at a cluster-level corrected threshold of $p < .05$.

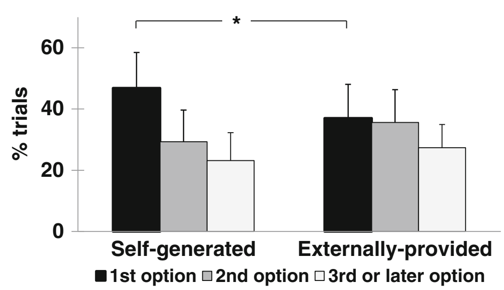

Fig. 6 Impact of option generation on choice behavior in the fMRI study: Distribution of choices across first and subsequent options (from dark to light blue) for the generate condition (left) and the control condition (right). Trials with only one generated option (only four trials across all participants) were excluded; all other trials were summed. Error bars denote standard deviations. Participants chose the first option significantly more often for self-generated than for externally provided option sets

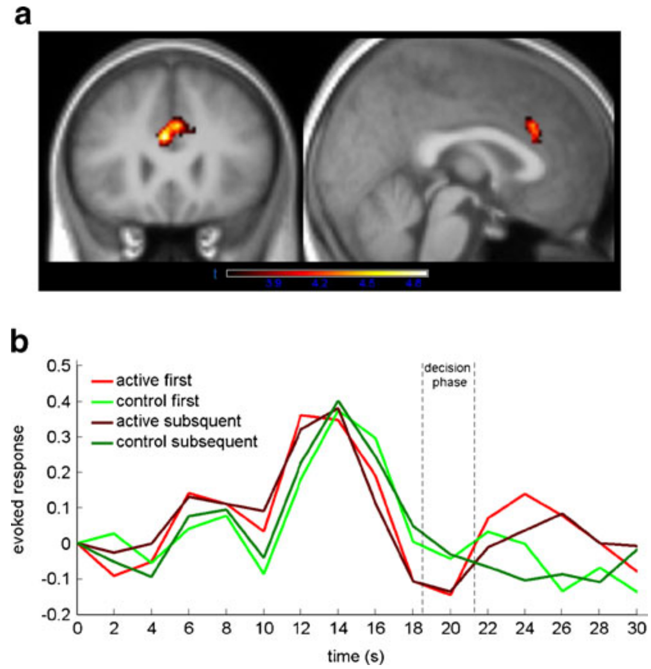

Fig. 7 Impact of option generation on the neural correlates of option selection in the fMRI study. **a** fMRI results showing the contrast decision between self-generated versus presented options. This comparison yielded activation in the dorsal anterior cingulate cortex. Image thresholded at $p < .001$ uncorrected, only the cluster significant at family-wise cluster-level corrected threshold of $p < .05$ is shown. **b** Time course plot of evoked responses (percentage of signal change) for the region depicted in Fig. 7a. Plots are separated according to condition (active/control) and option chosen (first/subsequent). Error bars are omitted for clarity. Dashed lines indicate the timing of the decision phase

Furthermore, we investigated whether ACC activation is dependent on the number of available self-generated or externally provided options. For this purpose, we computed a GLM with number of options as parametric modulator of the decision regressor. For the active condition, this parametric modulator did not yield any significant activation at a cluster-level corrected threshold of $p < .05$; that is, neural activation observed in the decision phase was not dependent on the number of options. Similarly, there was no significant parametric modulation in the control condition.

Neural correlates of the take-the-first heuristic

Finally, we addressed the question of whether or not the neural activity during option generation is related to choice patterns during subsequent option selection. Specifically, we investigated the neural correlates of the take-the-first heuristic (Fig. 8). For this purpose, we extracted mean percentage of signal change in the earlier task phase of interest from the left anterior

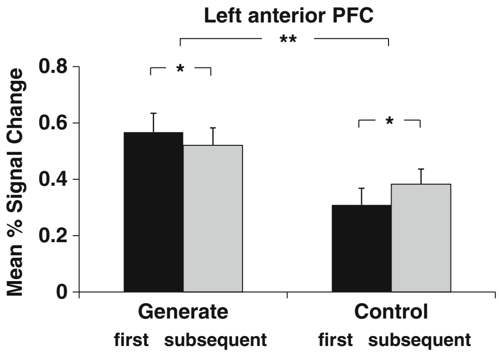

Fig. 8 Mean percentage of signal change extracted from the left anterior prefrontal cortex (PFC) region for each condition (generate/control) and choice (first option/subsequent options). Signal change in the lateral anterior PFC during option generation was significantly higher when participants subsequently selected the first option, as compared with later options, out of the self-generated option set

PFC region for each condition (generate/control) and choice (first option/subsequent options). We observed a main effect of condition, $F(1, 19) = 49.12$, $p < .001$, and an interaction between condition and choice, $F(1, 19) = 7.65$, $p < .05$. Post hoc tests showed that, in the generate condition, signal change in the left anterior PFC was stronger on trials where participants later selected the first option than when they selected subsequently generated options ($p < .05$). We also performed an exploratory whole-brain analysis of this interaction effect, which did not yield any additional activations at cluster-level corrected threshold.

In addition, we addressed the relationship between choice pattern and neural activation during the later task phase of interest, the decision phase. For this purpose, we extracted mean percentage of signal change from the ACC region described above for the decision phase in each condition (generate/control) and choice (first option/subsequent options). We observed a main effect of condition, $F(1, 19) = 11.32$, $p < .005$, but no main effect of choice, $F(1, 19) = 0.13$, $p > .1$. The condition × choice interaction effect reached trend-level, $F(1, 19) = 4.33$, $p = .053$, suggesting somewhat stronger activation during the active condition when the participant chose the first option generated.

Finite impulse response analysis over the whole trial

In order to assess condition-dependent changes independently of the shape of the canonical HRF, we performed an additional analysis modeling activation with finite impulse response functions. On the group level, the interaction of condition (active vs. control) and time yielded extensive activation of a broad set of brain regions shown in Table 2. Importantly, the brain regions found in this interaction encompass those found in our initial GLM analysis. More precisely, this includes the anterior prefrontal region found during generation versus reading of options and the anterior cingulate region found during decisions between self-generated and externally provided options. In addition, we observed extensive activation of posterior brain regions encompassing the regions found in the control (read) versus active (generate) contrast during the generation phase.

Table 2 Locations of significant activations for the condition × time interaction in the finite impulse response analysis (voxelwise threshold of $p < .05$ familywise error corrected; MNI coordinates, cluster size, and *F*-statistic are given)

Brain Region	MNI Coordinates (*x*,*y*,*z*)	Cluster Size	*F* (14, 540)	Contrast in Primary GLM Analysis
L putamen/ caudate	−14 12 2	1,155	14.73	–
R putamen/ caudate	16 12 2	969	13.04	–
L middle/inferior occipital gyrus	−44 −66 −12	2,004	12.04	Generate: control versus active
L middle frontal gyrus	−26 +50 +22	751	8.54	Generate: active versus control
R middle/inferior occipital gyrus	32 −92 −4	2,100	8.46	Generate: control versus active
L+R SMA/ACC	−4 12 50	1,372	7.34	Decision: active versus control
R middle frontal gyrus	+28 +48 +28	69	5.47	–
L superior parietal gyrus	−32 −58 52	119	5.17	Generate: control versus active
R middle temporal gyrus	60 0 −24	45	4.45	Generate: control versus active

Note. For brain regions also found to be significantly activated in the primary general linear model (GLM) analysis (see also Figs. 4 and 6), we provide the respective contrast in the last column of the table.

General discussion

Cognitive correlates of option generation

The main objective of the present research was to define the cognitive and neural correlates of option generation in everyday decision making. For this purpose, we first examined correlations between the quantity of generated options and performance on a broad battery of cognitive tests (Study 1). The main finding was a significant correlation with measures of retrieval from long-term memory and category fluency. In contrast, no significant correlation was observed with measures of creativity, letter fluency, and cognitive set shifting. Overall, this pattern of results suggests that the generation of options is more strongly associated with retrieval from long-term memory and with verbal fluency than with creative cognition and executive functions. This correlational structure might not generalize to option generation in all cases but is likely to depend on characteristics of the task employed, as we will discuss below.

As was stated in the introduction, this type of correlational analysis has not been previously performed specifically with respect to option generation. However, two studies from related lines of research provide important evidence. Channon and Crawford (1999) examined the generation of solutions for challenging real-world problems, most of which included a strong social component. In healthy participants, they observed significant correlations of the number of generated solutions with measures of memory recall, as well as set shifting and letter fluency. There are a number of critical differences to our paradigm that might account for the apparently stronger involvement of executive processes. Their situations were considerably more complex and were designed to reflect predicaments, which do not invite simple straightforward solutions. Furthermore, participants had considerably more time to generate possible solutions. The latter point has also been addressed with respect to the alternate uses task, in which participants have to generate unusual uses for everyday objects (Gilhooly, Fioratou, Anthony, & Wynn, 2007). Gilhooly and colleagues suggested that early in the task, participants mainly retrieve known uses from long-term memory and switch to other strategies only later in the task. Interestingly, category fluency was associated with generation of both known and new uses, while letter fluency was correlated only with generation of new uses. The correlations with fluency tasks observed in our study more strongly correspond to the known uses.

In summary, the stronger association with memory retrieval processes in contrast to executive processes, as found in the present study, has to be viewed in relation to the demands of the task. In our task, participants had to generate options for situations they might well encounter in their daily life. It is likely that, within the short available time frame in the present study, participants mainly retrieved known options from long-term memory. Hence, future research should manipulate the time frame participants are given to generate options and then test whether the correlation pattern is affected by this manipulation. In order to truly disentangle the underlying processes on the construct level, future research would have to use a larger task battery and employ latent variable analysis or alternative methods. Latent variable procedures require multiple tasks to measure each construct, and they statistically remove the error variance associated with the individual, imperfect tasks, retaining only the variance shared among all the tasks (Unsworth, 2010).

Neural correlates of option generation

In the fMRI study, we addressed the neural correlates of option generation. The comparison between generation of options and the control condition yielded a robust activation of the anterior PFC encompassing the lateral aspect of BA10 and extending into BA46. There is considerable evidence that this brain region is critical for guiding behavior in ill-structured situations (Burgess et al., 2009). A number of models have been put forward to account for the role of the anterior PFC in these contexts (Koechlin & Hyafil, 2007; Ramnani & Owen, 2004). One putative function of particular interest is the monitoring of internally generated information, which is certainly required in the case of option generation (Christoff & Gabrieli, 2000).

This hypothesis concerns a relatively broad set of tasks, while a more recent meta-analysis has associated the lateral part of the anterior PFC more specifically with retrieval from long-term memory, mainly with a high demand upon memory control processes (Gilbert et al., 2006). This is of particular interest in relation to our findings, because our behavioral data—albeit correlational—suggest a link between option generation and retrieval from long-term memory. Although different brain regions have been implicated in controlled retrieval from long-term memory, recent studies have commonly reported activation of the anterior ventrolateral PFC (Badre, Poldrack, Pare-Blagoev, Insler, & Wagner, 2005; Souza, Donohue, & Bunge, 2009). In comparison with our present study, they employed strict constraints on situations and stimulus material. Less constrained situations might require an even higher degree of control by the anterior PFC, because the retrieval cues do not lead to straightforward activation of the respective memory traces. In addition, more complex material—for example, involving social information—might also lead to recruitment of more anterior brain regions (Satpute, Badre, & Ochsner, in press). Thus, in our task using everyday situations, the correlational pattern from the behavioral study and the anterior prefrontal activation in the fMRI study are consistent with an account of option generation as controlled retrieval of options from long-term memory.

However, our fMRI design does not allow for a definite conclusion in this respect, because the control condition differed in more than one aspect from the generate condition. Thus, the observed differences between the conditions might be accounted for by processes other than retrieval from long-term memory. One approach would be to devise a different control condition with a requirement for retrieval of externally provided options. In this first fMRI study on the topic of option generation, we have decided to use only the two paradigmatic conditions; that is, either the options are directly available, externally provided options, or they have to be actively generated. Another way to establish retrieval from long-term memory as a key process during option generation would include an experimental manipulation of long-term memory demands. However, in the present task using everyday scenarios, it is extremely difficult to precisely estimate and manipulate memory load across conditions and participants. It may also be informative to investigate the effect of impaired memory retrieval after brain lesions on option generation.

An alternative explanation for the fronto-polar activation regards the dual-task requirement in the active condition, where participants have to both generate and memorize options. This dual-task requirement is likely to be lower in the control condition, because reading is a more automatic process and cognitive resources can be focused on memorizing the options. Dual tasks and, in particular, branching—holding in mind one goal while performing subgoal processes—have been linked to activation of the anterior PFC (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). The memory and dual-task accounts of anterior PFC activation are not mutually exclusive. In ill-structured real-world situations, agents will necessarily be required to both retrieve and maintain options for the subsequent decision.

Importantly, following the discussion of the behavioral study above, one should avoid overgeneralizing the neural findings. Quite obviously, the neural correlates of option generation are equally likely to be dependent on the type of situation and the associated constraints.

Option selection: The take-the-first heuristic

We also addressed the stage of option selection to test the hypothesis that choice behavior differs between self-generated and externally provided options. For this purpose, we first addressed choice behavior for self-generated options. In both studies, participants consistently selected the first generated option more often than all subsequent options. This finding shows that the take-the-first heuristic not only is applied in specific situational contexts, as suggested by previous studies (e.g., in sports), but also seems to be a general heuristic applied in a broad range of everyday situations (Johnson & Raab, 2003; Klein et al., 1995). In contrast to choice between self-generated options, no take-the-first heuristic was observed when participants chose between externally provided options.

This distinct pattern fits well with a memory account of the generation phase. Option generation has been conceptualized as a search through an associative network (Johnson & Raab, 2003). If agents have expertise with a situation, the preferred options are likely to have a high associative strength with situational cues and are thus likely to be retrieved first. Accordingly, a strong order effect on preference is expected for self-generated options, but not for externally provided options. Further evidence for a link between option generation and subsequent choice patterns comes from the neuroimaging data. The anterior PFC was more strongly activated in trials in which participants selected the first option from a self-generated option set. Thus, the neuroimaging data provide additional evidence that option selection might be, at least partially, predetermined by the processes occurring during the option generation stage. It is interesting to note that multivariate decoding methods have suggested the anterior PFC as a key region for prediction of subsequent decisions (Bode et al., 2011; Soon, Brass, Heinze, & Haynes, 2008). However, this early effect was reported only for multivariate, but not univariate, analyses, while we observed a clear anterior prefrontal activation increase using the latter approach. It has to be kept in mind that our experiment required conscious option generation in preparation of a subsequent decision, and not an unconscious process of intention formation. Nevertheless, it could be of high interest to apply multivariate decoding methods to option generation tasks. Independently of the underlying mechanism, our results strongly suggest that the take-the-first heuristic is applied specifically to decisions between self-generated options.

Neural correlates of option selection

On a neural level, option selection for self-generated options, in contrast to externally provided options, showed activation of the ACC overlapping with the rostral cingulate zone. It has to be stressed that the task requirement in the decision phase—indication of the choice by buttonpress—was similar in both conditions. Thus, the differential activation resulted solely from the preceding generation phase resulting in different types of options available for selection—self-generated versus externally provided ones. This brain region has been previously associated with internally selected "what" decisions (Krieghoff, Waszak, Prinz, & Brass, 2011; Mueller, Brass, Waszak, & Prinz, 2007). These studies have allowed participants to freely or internally select between options, but in contrast to our study, the available options were prespecified by the experimenter. It is striking that increasing degrees of freedom in both the selection stage in these previous studies and the generation stage in our study led to stronger decision-related recruitment of the dorsal ACC. Another explanation for the stronger anterior cingulate activation in the active condition regards the timing of the decision process. If participants had more time to decide before the actual decision phase in the control condition, less decision-related activation of the ACC would be expected in the decision phase. However, neither the whole-brain analysis nor the time course plots suggest stronger ACC activation during the generation phase in the control condition.

The exact functional role of the ACC in intentional action is a matter of considerable debate (Krieghoff et al., 2011; Nachev & Husain, 2010; Passingham et al., 2010). The literature offers at least two explanations for the increased ACC activation when deciding between self-generated options, in comparison with externally provided options. First, ACC activation has been observed when the decision about actions requires generation and monitoring of these actions (Walton et al., 2004). In our study, we have attempted to separate option generation from the actual decision. However, it is conceivable that self-generated options require increased monitoring during the decision process, because this information is relevant not only for future choices, but also for the future generation of options. This would also fit well with the role of this brain region in exploratory decision making (Rushworth, 2008). The present study does not allow a conclusion in this respect, because there was no feedback and subsequent optimization of performance. Second, several authors have raised the question regarding whether or not voluntary selection can be disentangled from conflict processing (Krieghoff et al., 2011; Nachev, Rees, Parton, Kennard, & Husain, 2005). This might also be a critical issue in our comparison, because the difference in preferences is likely to be less between self-generated than externally provided options and would thus result in higher conflict. However, if anterior cingulate activation is mainly conflict related, one might expect an increase when more options are available and when participants do not select the first option. We did not find evidence for either potentially conflict-related activation. Overall, we consider it unlikely that a pure conflict-based explanation can account for the observed pattern of results.

In order to reconcile these differing views, Holroyd and Yeung (2012) have recently proposed an innovative approach to anterior cingulate function based on hierarchical reinforcement learning. In their view, the ACC is responsible for the selection and maintenance of options, which they define in the hierarchical reinforcement learning context as extended sequences of primitive actions. While we did not formally define options and did not address learning from outcomes, this approach might, in the future, prove fruitful for quantitative modeling of option generation and subsequent choice. In sum, the present results clearly show that decisions between self-generated options can be distinguished on the behavioral and the neural levels from decisions between externally provided choice options.

Limitations

This study has a number of limitations, which are mostly related to the difficult balance between ecological validity and experimental control. Most important, the presently used task does not allow a strict separation of option generation and option selection. In other words, we cannot exclude the possibility that participants might have selected options during or directly after their generation. To minimize this possibility, in the present study, participants were under considerable time pressure during option generation, which renders a conscious deliberate decision process less likely to be performed concurrently. In addition, our distinct fMRI results suggest that different processes and brain regions are recruited during option generation and option selection. A critical issue here is the correlation between generation and selection regressors in the classical GLM analysis using the standard hemodynamic response function. However, the observed condition × time interaction in the finite impulse response analysis corroborates the notion that a separation of neural activation across the trial course is possible and valid, at least to some extent.

Nevertheless, it is quite likely that an evaluation of options may take place during option generation. This becomes even more important in real-world settings, where agents usually are not provided with a specific time frame for option generation. Instead, they have to decide on their own when to stop generating options; that is, they have to apply a stopping rule requiring ongoing evaluation of options. Further research is required to address this aspect of option generation (and selection) in real-world situations.

Conclusion

In almost all previous studies on decision making, participants had to decide between choice options provided by the experimenter. By contrast, in everyday decision making, individuals often have to actively generate choice options before making a decision. We employed a new experimental task in which participants had to generate options for real-world scenarios, and our results show that decision making and its neural correlates differ between self-generated and externally provided options. In conclusion, our results suggest that we need to be cautious when transferring the results of previous studies on decision making to ill-structured real-world situations.

More generally, it is interesting to note that almost all previous models on action control and decision making have neglected the option generation phase. The present results suggest that employing an expanded model of decision making, including the option generation stage, is both necessary and feasible. The fact that option generation has a clear impact on subsequent choice and its neural correlates underlines the need for an expanded model. Such an expanded model of action control and decision making has the potential to delineate research questions that have hitherto been neglected. For example, how is the option generation process influenced by higher-order goals? How is the quantity of option generation related to the quality of the final decision? How is the process of option generation related to goal shielding (Shah, Friedman, & Kruglanski, 2002)? These are important questions that can be answered only when considering an expanded model of decision making that includes an option generation stage.

Beyond expanding current frameworks for decision making, our findings open up new avenues for research on decision making and intentional actions in patients with neuropsychiatric disorders. In particular, apathy—which becomes most prominent in ill-structured situations—could be associated with a failure to generate options or to choose between self-generated options.

Interestingly, recent research has strongly associated apathy with lesions in the frontal pole and the ACC (Jorge, Starkstein, & Robinson, 2010), the brain structures subserving option generation and subsequent choice. Therefore, future research should examine whether clinical symptoms, such as apathy, are related to dysfunctions of option generation processes.

Acknowledgments The study was funded by the Volkswagen Foundation (Hannover, Germany) through the European Platform for Life Sciences, Mind Sciences and the Humanities.

Appendix

Scenarios (translated from German)

Scenarios employed in Study 1 and Study 2

1. Just in time for your day off, the sun begins to shine unexpectedly. What could you do?
2. After recovering from a severe flu, you're finally feeling better. What could you do?
3. You find your stolen bicycle on Ebay. What could you do?
4. You win an expensive Porsche. What could you do?
5. You threw a big party. The next day you have lots of food left over. What could you do?
6. You have been invited to a job interview and you want to prepare yourself for it. What could you do?
7. You would like to find out more about what your city has to offer in recreational activities. What could you do?
8. Your friends have come to visit and you would like to show them around the city. What could you do?
9. You are alone at the swimming pool. What could you do?
10. You come home late on Saturday evening and don't want to sleep yet. What could you do?
11. Today is your first day of vacation on a tropical island. What could you do?
12. You find a very old-looking painting in your attic. What could you do?
13. You find tickets for the movie theater for this evening. What could you do?
14. You're finished with your term paper two weeks earlier than planned. What could you do?
15. Due to the end of daylight-saving time, you got up an hour too early. What could you do?
16. At the checkout in the grocery store you are told that today everything is half off. What could you do?
17. You missed your train and have an hour to wait until the next train comes. What could you do?
18. You are in a new city and you have lost your way. What could you do?
19. You have had a headache for several hours which has been keeping you awake. What could you do?
20. You are standing in front of your apartment building and can't find your key. What could you do?
21. You want to bike to an appointment but you have a flat tire. What could you do?
22. You forgot about your best friend's birthday. What could you do?
23. In the evening you have a craving for chocolate but all the stores are closed already. What could you do?
24. Your best friend is lovesick and you want to distract him from it. What could you do?
25. You have been waiting for a friend in a bar for 20 minutes but he hasn't shown up. What could you do?
26. You have two tickets for the theater and your date cancels shortly before the show. What could you do?
27. You have invited friends over for dinner and you burn the food. What could you do?
28. When you arrive at the hairdresser's, you are told you will have to wait at least an hour for your turn. What could you do?
29. You can't fall asleep because you have an important appointment the next day. What could you do?
30. You want to read but your neighbor's music is so loud that you can't concentrate. What could you do?
31. It is the middle of winter. In the evening you notice that your heater isn't working. What could you do?
32. You want to grill today and notice that your grill is broken. What could you do?
33. You are talking on your cell phone. Suddenly the speaker is broken. What could you do?
34. You are at the beach and realize you have forgotten your sun screen in the hotel. What could you do?
35. You have a date in the evening and arrive at the restaurant 20 minutes early. What could you do?
36. You go to unlock your bicycle in order to bike home late at night and your key breaks off in the lock. What could you do?
37. You are on the way to a job interview and have forgotten the exact address of the company. What could you do?
38. You are stuck in your car in a traffic jam. What could you do?
39. Your boss explains your assignment to you. After he leaves, you can't seem to remember all of the details. What could you do?
40. After getting back from grocery shopping, you realize you've forgotten an important ingredient for your lunch. What could you do?
41. You were out with a friend and he wants to drive home intoxicated. What could you do?
42. You are at home and want to cook when the power suddenly goes out. What could you do?
43. You share a room with your friend while on vacation and he snores so loudly that you can't sleep. What could you do?

44. When you arrive at the swimming pool, you realize you've forgotten your towel. What could you do?
45. It's Sunday morning. You are looking forwards to a bowl of cereal and realize the milk has gone bad. What could you do?
46. It's your birthday, but you're sick in bed. What could you do?
47. You see the lead singer of your favorite band in a bar. What could you do?
48. You would like to treat your friend to something nice after his graduation from college. What could you do?
49. You want to help a friend quit smoking. What could you do?
50. Your friends helped you move and you want to thank them for it. What could you do?
51. You want to go to the movies with your friends, but tickets are sold out. What could you do?
52. You were going to go swimming with friends today, but it's raining. What could you do?
53. You drink a beer at a bar. As you're about to pay, you notice that you've forgotten your wallet. What could you do?
54. You're sitting on the train and you're very tired. You want to stay awake so you don't miss your station. What could you do?
55. While working in a group, one person is barely contributing. What could you do?
56. While on vacation you want to go on a bike tour, but it's been raining the entire morning. What could you do?
57. Someone calls you and wants to come by in half an hour, but your apartment is a mess. What could you do?
58. You want to watch a movie, but at the movie rental store you see that all the copies of the movie are already gone. What could you do?
59. You're in a bad mood and want to cheer yourself up. What could you do?
60. You're over at your friends' house and they're in a relationship. Suddenly they start arguing. What could you do?

Scenarios employed in Study 1 only

61. You got a haircut, and you are completely unhappy with the result. What could you do?
62. You are at a restaurant with your parents. A friend calls you, she/he is crying and very upset. What could you do?
63. You are accidentally trapped in a department store. What could you do?
64. You are accused of having cheated on an exam. What could you do?
65. Your friends want to go out with you, but you have to get up early the next day. What could you do?
66. At a a party you accidentally pour red wine on a white carpet, but nobody seems to have noticed your mishap. What could you do?
67. You have borrowed an umbrella from a friend. When you want to return it you realize it's broken. What could you do?
68. You are in the theater with a friend. You find the play very boring but the it still lasts for about 1 hour. What could you do?
69. The shirt that you planned on wearing the next day is dirty and the washing machine is broken. What could you do?
70. You have borrowed an exciting book from the library. Near the end you realize that the last few pages are missing. What could you do?

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